Bull. Disas. Prev. Res. Inst., Kyoto Univ., Vol. 19, Part 3, No. 160, February, 1970

Investigation of Microearthquakes

—On the Accuracy of Hypocenter Determination—

By Michio HASHIZUME

(Manuscript received August 30, 1969)

Abstract

The accuracy of hypocenter determination of microearthquakes is the best when two parameters, crustal structure and origin time are fixed. The crustal structure can be put as an approximated one and the origin time can be determined independently. The error by setting two parameters fix is less than the error by other methods. By other methods the accuracy of focal depth does not stand for general usage in the study of microearthquakes and uniform seismicity can not be studied. Furthermore we discussed the possibility of revising the crustal structure by using microearthquakes.

1. Introduction

The accuracy of hypocenter determination is much affected by the system of observation, the method of hypocenter determination and the interpretation of results. As for the observation system following items are concerned :—

a. the pattern of observation,
b. the shape and size of the observation network,
c. the accuracy of observation and seismogram reading,
d. the crustal structure and local traveltime anomaly.

As for the method of hypocenter determination the following items are concerned :—

a. the procedure of determination,
b. the unknown parameters included.

As for the interpretation of results the following items are concerned :—

a. the necessary elements,
b. the value of dislocation of hypocenter in a certain value of observational error.

It is impossible to make general descriptions on these problems. But focussing emphases mainly on the observation and seismogram reading, time accuracy is restricted within a certain value. When we are concerned with a microearthquake or ultramicroearthquake, the possible epicentral distance observed is limited at most within 150 km and the number of observation stations is not so many.

There are some methods that are used only temporally or supplementary for the hypocenter determination such as the tripartite method[1] and so on, but the accuracy of these methods is generally worse than those discussed later.

As a typical example, we discuss these problems in connection with the network of the Tottori Microearthquake Observatory of the Disaster Prevention Research Institute of Kyoto University. It does not necessarily mean giving up general discussions, and we shall further discuss a better system for observation and device for the improvement of the accuracy of hypocenter determination.

We have described our network already[2]. The locations of observation stations are tabulated in Table 1 and Table 3.*) In this paper our discussions are mainly concerned to the five stations in Table 1.

The time accuracy of observation and seismogram reading is within ± 0.05 sec for P onset time and within ± 0.1 sec for S onset time. Traveltime anomalies are within ± 0.1 sec for each station.

Setting the possible area of observation within ± 150 km, earthquakes of which magnitudes are more than 1.2, are observed uniformly. (We have presented some questions about the definition of magnitude of microearthquake.[2])

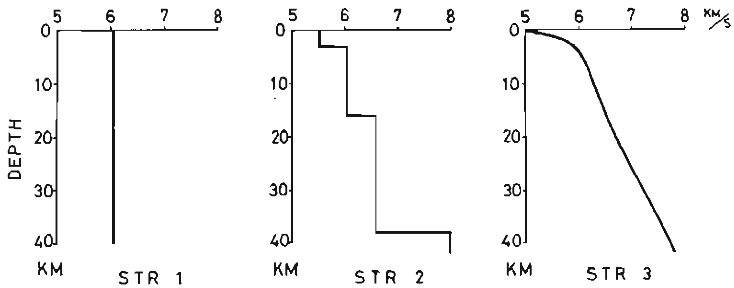

Fig. 13 Crustal structure used in this paper.

We use three types of crustal structures shown in Fig. 13. Among these structures STR 2 is the same structure as that shown in Fig. 4 and it is considered to be the first approximation structure under our observation region.[4]

On the above situation we discuss the accuracy of hypocenter determination of microearthquakes which occur mainly in the crust. Especially our interest is in the accuracy of the focal depth, because from our following discussions the epicenter is determined with fairly good accuracy for the general sense of seismicity, but although it is very important to know the focal depth accurately to research the various nature in the crust, the accuracy of its determination depends very much on the given conditions.

The notations used in this paper are the same as those in the preceding paper of the same title.[2]

2. The Accuracy of Hypocenter Determination

It is considered that the elements of hypocenter determination are as follows :—

a. origin time,
b. epicenter,
c. focal depth,
d. areal stability of accuracy.

In determining the hypocenter some parameters are unknown. Generally

*) The numbers of Tables and Figures are in series in the articles of the same title.[2,3]

these parameters are origin time, hypocenter and crustal structure. Among these, crustal structure can be usually estimated as the first approximation. The origin time can be calculated fairly exactly from the Poisson's ratio σ as an independent parameter on the concerning region using the P and $S-P$ time of many earthquakes. That is the origin time is obtained from the average value of $P^0{}_j$ of the following equation :—

$$P^0{}_j = P_j - \mathrm{A}(S-P)_j \tag{2-1}$$

where $$\mathrm{A} = \sqrt{1-2\sigma}/(\sqrt{2-2\sigma} - \sqrt{1-2\sigma})$$

Theoretically only one datum of $(S-P)_j$ time is sufficient to calculate the origin time. In a case that the Poisson's ratio is not uniform over the area or depth concerned the equation (2-1) becomes complicated, but it is possible to know the origin time by iteration, putting as the first approximation the initial value of the origin time and the determined hypocenter.

Then the problem of the accuracy of the origin time is reduced to the evaluation of the accuracy of identification of the S phase, and how to determine the hypocenter when no S phase can be read.

Now we discuss the effects of treatment of these parameters on the accuracy of hypocenter determination and further research for the optimum method for hypocenter determination.

A) *In a case that unknown parameters are the hypocenter, origin time and crustal structure*

Satô (1965) discussed the accuracy of hypocenter determination in this case, assuming a homogeneous semiinfinite elastic structure by the Monte-Carlo method.[5] Applying his results to our network shown in Table 1, in which the span between nearest station is about 30 km, the observational error is about 0.1 sec and the number of stations is five. The average accuracies of hypocenter determination for the earthquakes which occurre arround this network are obtained as follows :—

epicenter : about several kilometers,
focal depth : impossible to discriminate whether the earthquake occurred in crust or in mantle,
velocity : 0.5∼1 km/sec,
origin time : 0.5∼1 sec.

In some cases there are sorts of singular points and near these points the accuracy is much worse than above values.

In usual cases we can estimate velocity within an accuracy of 0.5∼1 km/sec, and it is useless to determine the velocity by each earthquake.

As we shall discuss later the crustal structre can be revised starting from the first approximation. And the existence of singular points prevents to make a uniform seismicity map.

Now we shall discuss the accuracy of hypocenter determination when the crustal structure is already known.

The procedure to calculate the accuracy is as follows. At first setting a hypocenter, we can calculate the theoretical traveltimes to each station when the crustal structure is known. Observational data have some errors added to these traveltimes. Thus when we determined the hypocenter using these observational traveltimes, or P onset times when origin time is unknown, the hypocenter or origin time are determined in a certain error domain.

The accuracy of hypocenter determination is expressed as this hypocenter and origin time domain due to a certain observational errors.

The method to determine the hypocenter was described in the preceding paper.[2]

The accuracy of focal depth is expressed in figures shown later in such a manner that the upper limit of focal depth (some times it is equal to the surface) is shown by dotted narrow curves and lower limit of focal depth by solid broad curves and numerals on contours are in kilometer. As for the epicenter, three dimensional expression is necessary, but conventionally it is represented by the largest dislocation d of the epicenter which is classified in figures, when it is not mentioned especially, in such a manner that the dislocation more than 5.0 km is shown by thick dotted area, between 1.5 and 5.0 km by thin dotted area and within 1.5 km by blank area. Observation stations are shown by solid circles. As for far outside the network some descriptions are deleted.

B) *In a case that unknown parameters are the hypocenter and origin time, and the crustal structure is known*

The accuracy of hypocenter determination in this case is shown in Figs. 14 a, b, c, d when standard deviation s on determining the hypocenter is 0.1 sec for a given focal depth. Crustal structure used for calculation are STR 1 in Figs. 14 a, c and STR 2 in Figs. 14 b, d. Figs. 14 a, b describe the accuracy of the focal depth and Figs. 14 c, d describe the accuracy of origin time and epicenter with numerals on contours in second.

Although in this case accuracy is improved as compared to the former case, the contours look fairly complicated and it seems difficult to know the uniform seismicity.

The error domains of the focal depth, epicenter and origin time go over 10 km, 5 km and 1 sec respectively even in the area not so far from the network.

The effect of the crustal structure on the accuracy is complicated, but in general the focal depth is determined comparatively well for STR 2 rather than for the simple structure of STR 1.

This method is available in a case that S phases can not be read at any station, or in a case that epicenters are confined to a narrow area and the identification of S phases is difficult, such as with volcanic earthquake or swarm earthquake. In the latter case the origin time is determined within 0.5 sec and the epicenter is within 1.5 km, but the focal depth does not stand for general usage.

An example of hypocenter determination in this case is shown in Table 10. The hypocenter is a quarry blast at Tomieda near Tottori city. From this table we can see easily that the origin time and focal depth can not be determined with good accuracy.

General speaking, the accuracy of origin time by this origin time unknown

Table 10. An example of the accuracy of hypocenter determination in a case that the origin time is unknown. The hypocenter is a quarry blast at Tomieda, near Tottori city. The observation points are the five stations in Table 3.

	MZ	FO	OY	HM	IZ
P	39.60	34.00	36.85	43.14	43.22

ORIGIN	H	X	Y	s
32.10	0.0	− 6.71	42.66	0.09
32.02	2.0	− 7.56	44.23	0.10
32.10	3.0	− 7.76	43.73	0.09
31.91	5.0	− 8.26	44.29	0.11
31.98	6.0	− 8.26	44.30	0.09
31.91	7.0	− 8.56	44.52	0.10
31.83	8.0	− 8.89	44.86	0.10
31.73	9.0	− 9.23	45.26	0.11
31.61	10.0	− 9.65	45.67	0.11
31.49	11.0	−10.05	46.18	0.12
31.33	12.0	−10.67	46.85	0.13
31.20	13.0	−11.22	47.29	0.14
Shot point MISSED	0.0	− 7.12	41.69	

P : *P* times of five stations.
Origin : Origin time determined.
H : Focal depth determined.
X, Y : Coordinate of epicenter determined based on Table 3.
s : Standard deviation on determining hypocenter; cases only less than 0.15 sec are listed.

method can not be reduced to less than 0.5 sec.

The results of the analyses of about 1500 earthquakes by our network are as follows:—

coefficient A in equation (2-1): 1.4083 ± 0.0015

standard deviation of the error of origin time: $0.18/\sqrt{N}$

(N is the number of stations where the *S* phases are read at each earthquakes, in our case N=3.2 in average)

the number of earthquakes of which *S* phases could not be read at any stations: 8

In these results the accuracy of the origin time is the average value of the standard deviations of $(P^0{}_j - P^0)$ for each earthquake and we can consider it as one of the indicators of the accuracy of the origin time.

The error of origin time due to the coefficient A that is concerned with Poisson's ratio is at most 0.02 sec at 150 km of the epicental distance.

As shown by these results, we can determine the origin times safely less than the above 0.5 sec.

C) *In a case that the unknown parameter is the hypocenter, and the crustal structure and origin time are known*

The accuracy of hypocenter determination in this case is shown in Figs. 15 a, b, c for a given focal depth. The crustal structure used for the calculation is STR 1 for Fig. 15 a and STR 2 for Figs. 15 b, c. Standard deviation s on determining hypocenter is set as 0.10 sec for Figs. 15 a, b and 0.15 sec for Fig. 15 c. For $s=0.10$ sec the accuracy of the focal depth is within 2 km, epicenter dislocation is within 1.5 km in and near the network for each focal depth except the earthquake shallower than 10 km of which the takeoff angles to the stations observed are nearly horizontal, then there are little traveltime differences for focal depth shallower than 10 km. It is concluded that it is difficult to classify by depth the earthquakes shallower than 10 km by the seismic network of 30 km span or so.

A characteristic feature is that the accuracy of the focal depth is much better for STR 2 than for STR 1 in the further area of network. It may be caused by the reason that the traveltime changes sensitively by focal depth affected by the refraction at the layered boundary in a certain epicentral range. Conversely, in this epicentral range the accuracy of focal depth is very sensitive to the crustal structure.

Supposed that the actual structure is approximately like STR 2, and the earthquake occures within the area of ± 100 km, the hypocenter is determined with an accuracy of $\pm 3 \sim 5$ km of the focal depth and of 1.5 km of the epicentral dislocation except for very shallow one. Even if it extends to the epicentral distance of 150 km, epicentral dislocation does not exceed 3 km.

Epicentral dislocation for $s=0.15$ sec is not shown in Fig. 15 c, but is considered to be nearly 1.5 times as large as that in the case $s=0.1$ sec. When we discuss the focal depth, it is desirable to keep the time accuracy within 0.1 sec.

In the course of the observation of an earthquake, it is not always observed at all of the five stations. The smaller the magnitude the narrower the observable area becomes. In Figs. 16 a, b the accuracy determined by four stations are shown for STR 2, $s=0.1$ sec and focal depth 10 km. At a glance at this figure the good accuracy domain reduces a little as compared to the case of the five stations, but in general great changes are not seen.

In Fig. 17 the accuracy of the hypocenter determined by ten stations, that is in most cases rather large earthquake, is shown for STR 2 and $s=0.1$. In natural reduction the accuracy improves fairly well, but even in this case of ten stations the focal depth of the earthquake shallower than several kilometers can not be determined accurately.

By this method the hypocenter can be determined principally by three stations. Of course the larger the number of stations carring out observation the better, but the accuracy of the hypocenter is not so sensitive to the number of stations.

Theoretically except special cases unknown parameters do not decrease further more. Thus when we want to get some information about the earthquake occuring in the uppermost crust, the span of seismic network should be dense enough to be comparable to the focal depth.

The next problem is how the origin time error affects the accuracy. As mentioned above Poisson's ratio is known in sufficient accuracy. Then the accuracy of the origin time is affected by the S phase identification. From the preceding discussions, the standard deviation of the error of the origin time is

$0.18/\sqrt{3.2}$, that is about 0.1 sec. If we set the error of origin time ± 0.2 sec, error of 95 % of earthquakes is included in this value.

In this case of the ± 0.2 sec the accuracy of hypocenter deternination is shown in Fig. 18 at a depth of 10 km. Accuracy of focal depth is within ± 3 km at the central area of network while within ± 1 km for the outside of network. This may be due to the situation of stations and the error of the origin time affects only on the vertical direction when an earthquake is surrounded by the network stations. The dislocation of the epicenter is at most 0.2 sec$\times P$ wave velocity, that is within 1.5 km. These reductions are supposed to show similar feature for any focal depth.

Now we can safely say the method of hypocenter determination by origin time fixing is the best method for all the hypocenter elements.

We have assumed that the crustal structure is known, but we do not know the real feature and on determining the hypocenter we used only an approximated one.

Figs. 19 a, b show the accuracy of the hypocenter in this case. Fig. 19 a is the case that the real structure is STR 2 and the assumed one is STR 1 (we express as STR 1—STR 2 hereafter) and Fig. 19 b is the case of STR 2—STR 3. In the ruled area the standard deviation on determining hypocenter is more than 0.1 sec. The effect of the difference of the structure on the hypocenter is not so large between STR 2 and STR 3, except for the area where the traveltime difference of refracted wave affects sensitively as we have mentioned already. But the effect is very grave in the case of STR 1—STR 2 in the area not so fo far from network. The discrepancy of the focal depth exceeds 10 km and the epicenter 5 km, for the earthquake of which the focal depth is more than 15 km.

We must have therefore, information about the crustal structure in such a degree of accuracy as to be able to discriminate STR 1 from STR 2. Fortunately concerning our region this condition is satisfied and the effect of structure on the accuracy seems to be not so large.

In these calculation it was unexpected that the standard deviation in determining the hypocenter is so insensitive to the structure. Maybe the calculated hypocenter, moving itself, is adjusted to the traveltimes.

So far as the crustal structure is not accurately known the standard deviation in determining the hypocenter is not a good indicator of the accuracy of the hypocenter.

3. On Revising the Crustal Structure

From the preceding discussions the calculated hypocenter dislocates to fit itself to the traveltimes of the assumed crustal structure. And the standard deviation on determining the hypocenter changes a little. Two possibilities are inferred by using the above reductions to revise the crustal structure.

The first is the statistical method using the average value of the standard deviation of a great number of earthquakes and we consider the model of the least value of the average standard deviation as the most possible structure. The average standard deviations of the preceding calculation on STR 1—STR 2 and STR 2—STR 3 are listed in Table 11 for some focal depths. In this calcula-

Table 11. Standard deviation on determining hypocenter by applying assumed crustal structure instead of the real one. STR A—STR B means that the real one is set as the STR B model and the assumed one is the STR A model. Earthquakes are supposed to occur uniformly on the plane of a given depth in the area concerned. Mean values are weighted by seismicity histogram in Fig. 11.

DEPTH	STR 1—STR 2	STR 2—STR 3
0.0	0.045	0.032
5.0	0.028	0.033
10.0	0.032	0.057
15.0	0.037	0.065
23.0	0.044	0.067
MEAN	0.033	0.048

tion the earthquake is supposed to occur uniformly on the plane of a given depth in the region concerned. Mean value is weighted by a focal depth seismicity histogram in Fig. 11.

As an example, the calculation of STR 1—STR 2 at the depth of 15 km gives the mean value of the standard deviation of 0.037 sec. In this value the error by traveltime calculation, error by final grid spacing of 0.2 km in epicenter calculation and the error by depth interval of 1 km are included. Considering these errors, the mean value of 0.037 sec may decrease to 0.02 sec or so.

When we set a population in Table 5 a, several tens of earthquakes occurring at this depth is enough for the difference of the mean value of the standard deviation of 0.02 sec to be significant value in a 90 % confidence band.

The second method is possible on the condition that there are several independent observation stations outside the network. The time accuracy at the observation stations is not necessarily expected in such a good condition as at the network stations.

As the accuracy of the hypocenter determination is not so sensitive to the number of stations, it is not so effective to discuss the standard deviation on determining the hypocenter by using these stations.

Now we put $(O-C)_j$ as follows:—

$(O-C)_j$ = Traveltime observed − Traveltime expected (3-1)

where Traveltime observed = P onset time − Origin time, and it means traveltime from real hypocenter to a station, passing through the real structure. Traveltime expected means the traveltime passing through the assumed structure to a station from the hypocenter determined.

In Figs. 20 a, c several examples of calculations of $(O-C)_j$ are plotted. In Fig. 20 b the observation stations (the stations used to calculate the hypocenter are marked by solid triangles and the independent stations by solid circles) and the epicenters (crosses) at which the numerals mean the coordinate referred to Table 3 are shown.

Each figure contains several little figures. In these figures the ordinate is for $(O-C)_j$ in second and abscissa is for epicentral distance in kilometer. Little solid circles are the $(O-C)_j$ at the observation stations used to determine the hypocenter and the large solid circles are the $(O-C)_j$ at independent stations. The location of the epicenter is shown on the upper most side of each figure referring to Fig. 20 b. All the real focal depths are set as 15 km. The focal depth determined is shown as D in figure, but this value does not necessarily coinside with real depth.

The common facts reduced from these figures are as follows:—

a. $(O-C)_j$ at the station used to calculate the hypocenter seems to have no definite tendency.

b. For the crustal model adopted here, $(O-C)_j$ at independent station is in general plotted at the side of the minus region.

c. $(O-C)_j$ at the independent station of short epicentral distance and sometimes middle epicentral distance is plotted as a large value, but this value varies complicatedly with the relative situation of the epicenter and station or the difference of crustal structure.

d. $(O-C)_j$ at the independent station of long epicentral distance is also very large and it seems to imply the real velocity of the crustal structure.

It is easy to distinguish between STR 1 and STR 2. $(O-C)_j$ greater than 0.5 sec, of course, go over the error limit of observation and origin time. At the depth arround 15 km the apparent velocity for STR 1 is 6.05 km/sec and 6.6 km/sec for STR 2, for the epicentral distance between nearly 50 km and 150 km.

As for STR 2—STR 3 in the epicentral distance between 50 km and 100 km some $(O-C)_j$ are large (see 10·10 in figures) this is due to the velocity jump at 16 km in STR 2, and between 100 km and 150 km (the deepest point of the ray path is about 17 km and 29 km, respectively) apparent velocity expected from STR 2 is about 6.6 km/sec and about 7.0 km/sec from STR 3. This is clearly read in these figures. It is possible to distinguish the three structures given in this paper without explosion seismology. We know that interpretation of the traveltime by explosion seismology is not unique[6], and above facts suggest by adding some devices to reduce $(O-C)_j$ minimum that we can study detailed crustal structure compensating the result by explosion seismology. For this purpose it is desirable to set temporary observation stations around the main network over some periods.

We shall discuss this problem later[7].

4. Conclusions

The following conclusions are summarized from the above discussions.

We find that the accuracy of hypocenter determination is best when two parameters, crustal structure and origin time, are fixed. In this case the crustal structure can be assumed as the first approximation, and the origin time is determined independently by equation (2-1) using P_j and $(S-P)_j$ time and preliminary calculated Poisson's ratio. Although the accuracy of hypocenter determination varies according to the given conditions, the accuracy is best and the seismicity can be discussed in most uniformly as compared to the other methods.

In the case that the origin time can not be independently determined, that is the S phase can not be read at any station, the accuracy of the origin time and focal depth does not stand for general usage in the study of microearthquakes and uniform seismicity can not be studied.

The method of hypocenter determination setting crustal structure and origin time unknown can not be used for the study of microearthquakes.

The error of origin time determining by equation (2-1) is not large as compared to the error by other methods and does not affect the accuracy of hypocenter determination so much.

The accuracy of hypocenter determination by setting the approximated crustal structure is not good far outside the network if the difference between the real and the assumed structure is great. But the structure can be revised, on the other hand, by using the determined hypocenter.

One method is to search for a model to make the standard deviation minimum on determining hypocenter. By this method we can distinguish the three structures in Fig. 13.

Another method is to observe earthquakes independently outside the network and to make the $(O-C)_j$ defined in equation (3-1) minimum. It is confirmed that the crustal structure can be studied by microearthquake besides explosion seismology. It is very useful to set temporary stations outside the network in order to know the crustal structure accurately.

It is desirable in observing microearthquakes to keep the time accuracy within 0.1 sec. The seismic network should cover an area more than a certain value, but if the mesh is rough the accuracy of the focal depth is sacrificed for shallow earthquakes. On the other hand, accuracy is not improved so much in accordance with the number of stations.

To read the *S* phase is important to determine a hypocenter accurately so the ideal observation should be carried out by three component seismographs.

Acknowledgements

The author expresses his sincere thanks to Professor Y. Kishimoto of Kyoto University for his guidance and encouragement.

He also expresses his hearty thanks to Dr. T. Mikumo of Kyoto University and Dr. S. Asano of Tokyo University for helpful advice about the traveltime computations.

Financial aid was granted by the Science Research Fund No. 96059.

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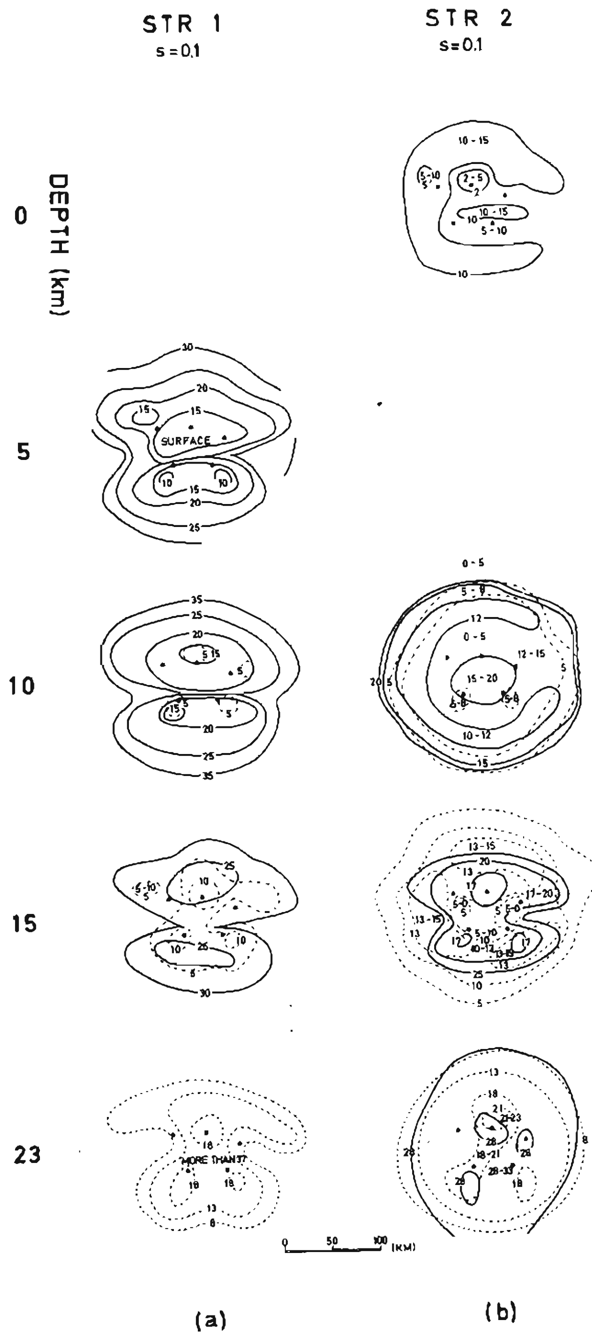
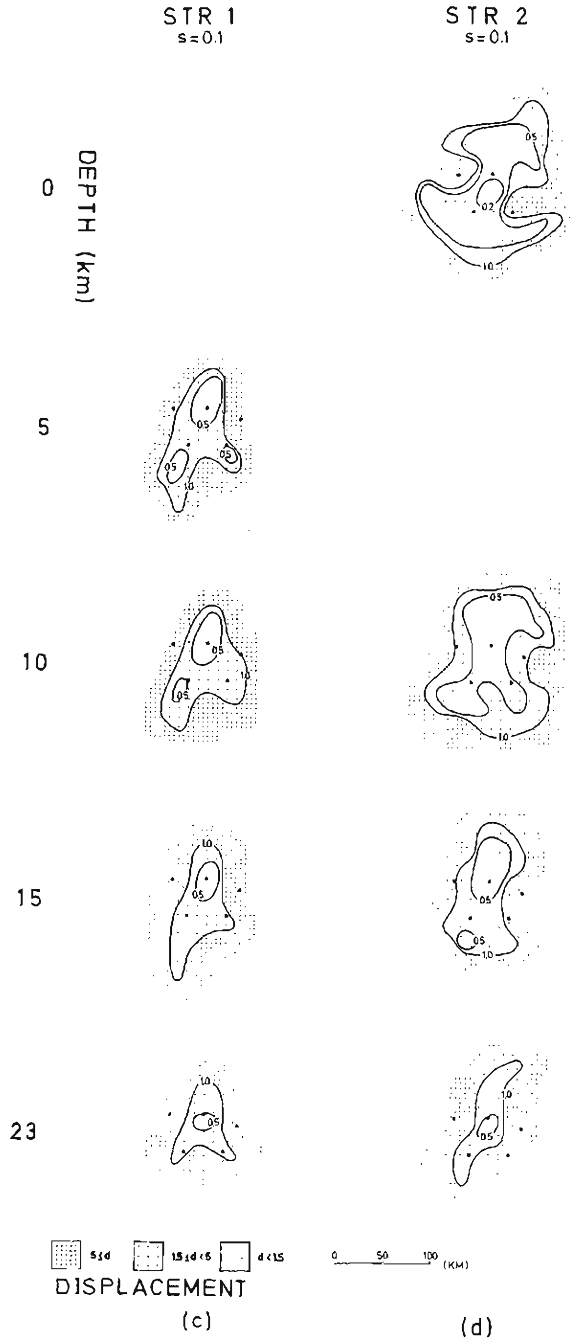


Fig. 14 a, b, c, d. Accuracy of hypocenter determination when the crustal structure is assumed. Figs. a, b show the accuracy of the focal depth and Figs. c, d show the accuracy



(c) (d)

of the epicenter and origin time. The notations are described in the body of this paper.

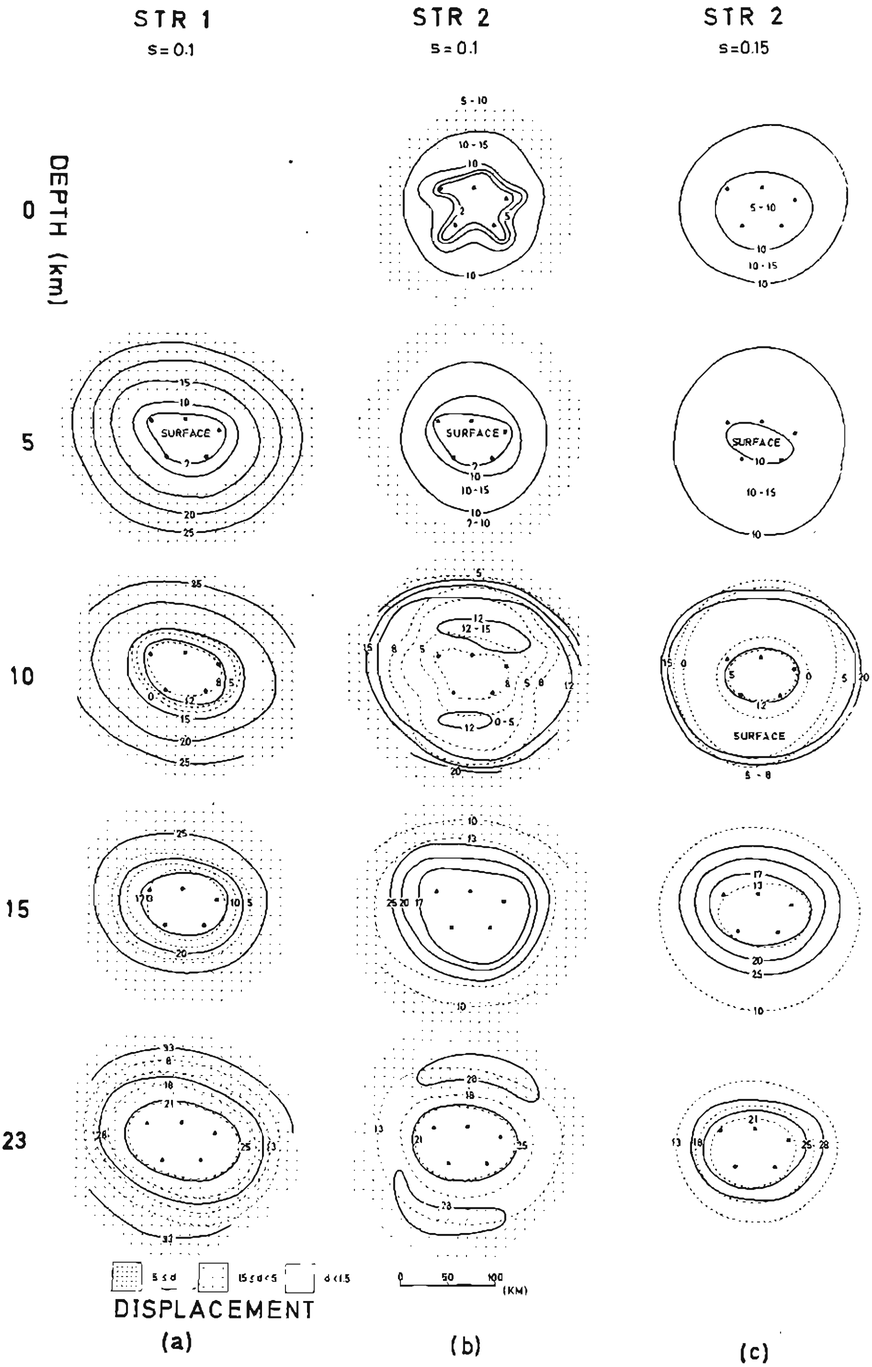


Fig. 15 a, b, c. Accuracy of hypocenter determination when the origin time is independently determined and crustal structure is assumed. In Fig. c the accuracy of the epicenter is not shown. The notations are described in the body of this paper.

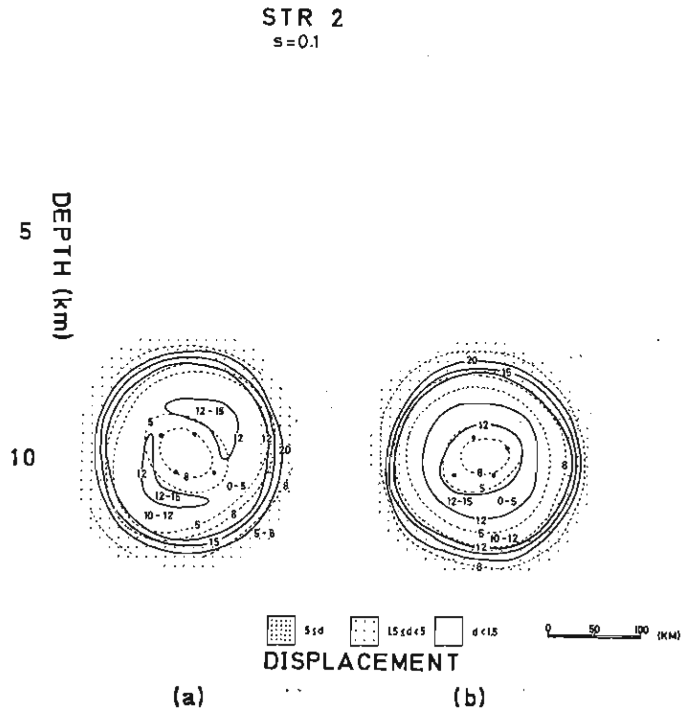


Fig. 16 a, b. Accuracy of hypocenter determination when the origin time and crustal structure is fixed and the number of stations is four. The notations are described in the body of this paper.

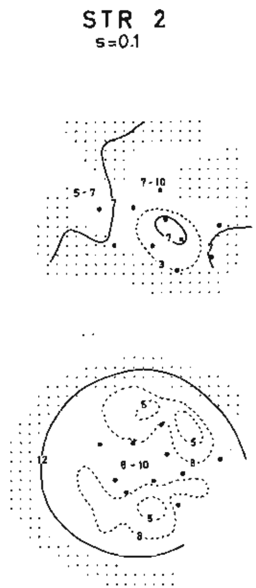


Fig. 17. Accuracy of hypocenter determination when the origin time and crustal structure are fixed and the number of stations is ten. The notations are described in the body in this paper.

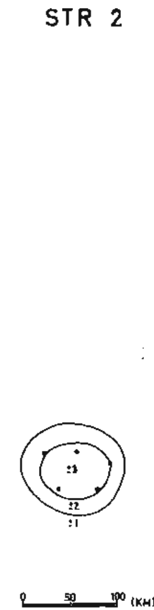


Fig. 18. Effect on the hypocenter when the error of the origin time is ±0.2 sec by the method of the origin time and crustal structure fixed. The notations are described in the body of this paper.

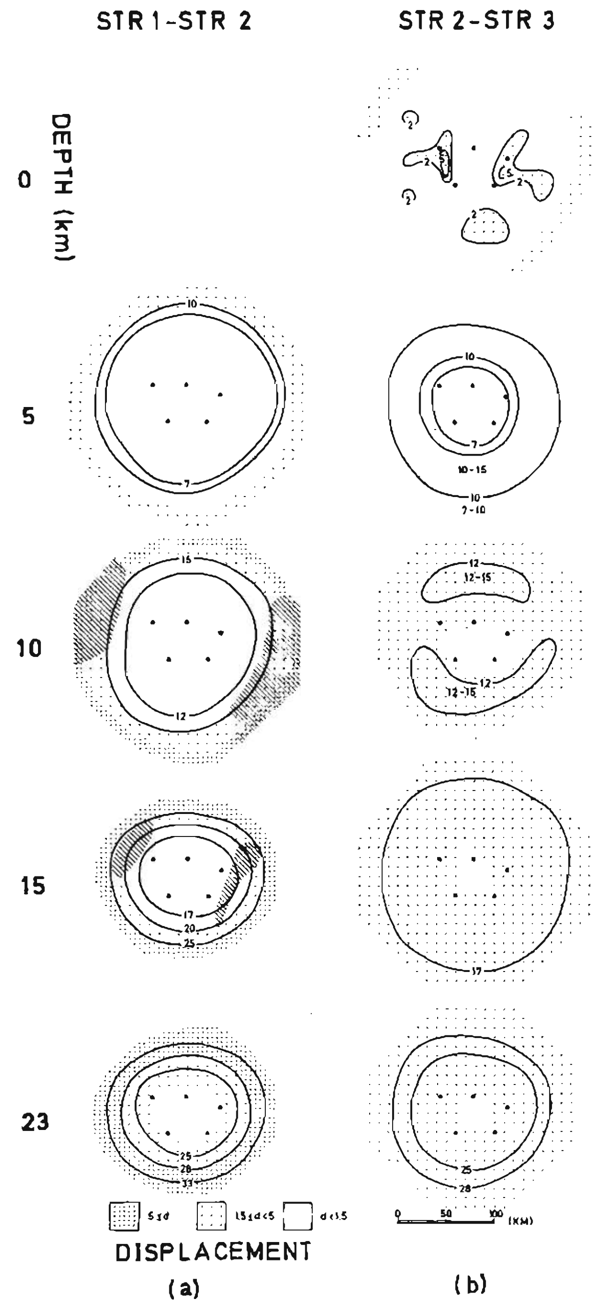


Fig. 19 a, b. The accuracy when the hypocenter is determined by the different structure in stead of the real one. The ruled area shows the region where the standard deviation on determining hypocenter is more than 0.1 sec. Notations are described in the body of this paper.

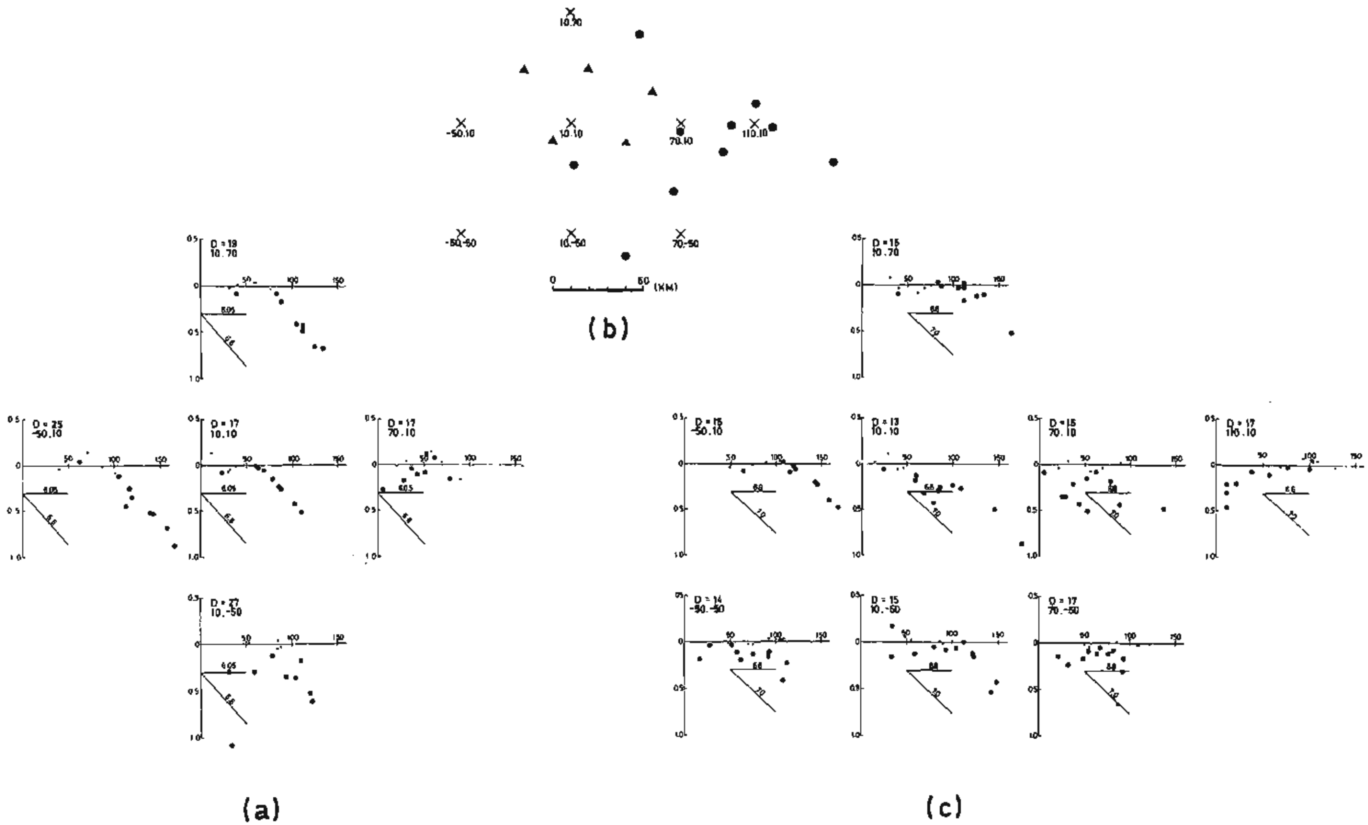


Fig. 20 a, b, c. Expected $(O-C)_j$ at the observation stations when the hypocenter is determined by the different structure in stead of the real one. Small solid circle: $(O-C)_j$ at network station. Large solid circle: $(O-C)_j$ of independent station. Fig. b shows the location of stations and epicenters. Solid Triangle: network station. Solid circle: independent station. Cross: epicenter. Other notations are described in the body oy this paper.